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Contributions of the x-15 program to lifting entry technology

CONTRIBUTIONS OF THE X-15 PROGRAM TO LIFTING ENTRY TECHNOLOGY

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INTRODUCTION

1 Although the X-15 was not designed to investigate the problems of orbital
2 lifting reentry, it is the first research vehicle capable of piloted flight
3 outside of the sensible atmosphere as well as within the atmosphere and,
4 therefore, is capable of lifting entry. In addition to providing research
5 information concerning hypersonic flight, the X-15 has provided information
6 applicable to atmospheric lifting entry and recovery.

7 Similar to other contemplated entry vehicles, the X-15 reenters as an
8 unpowered glider. Because its speed capability is much lower than that of
9 orbital vehicles, the X-15 enters much more steeply, which results in shorter
10 entry time (fig. 1) and, in some respects, a more severe entry. The steeper
11 the entry, the more rapid will be the changes in important control parameters.
12 This meant a formidable task for the X-15 design engineer and a rather severe
13 control task for the pilot, particularly in abnormal or emergency conditions.

14 Perhaps the entry research potential of the X-15 can best be illustrated
15 (fig. 2) by comparing the X-15 velocity with that of an orbital lifting entry
16 vehicle with similar characteristics, a W/C_{DA} of 200 to 600 and a lift-drag
17 ratio of 1 to 2.

18 Piloting experience has been obtained with the X-15 in several regions
19 of interest, for example, in regions of essentially zero dynamic pressure and
20 regions of high dynamic pressure, up to about 2,000 psf. Inasmuch as the Mercury

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1 program has supplied more significant control data than the X-15 at zero dynamic
2 pressure, this region will not be considered in this paper. Control in regions
3 of low and high dynamic pressure will be discussed and, based on this experience,
4 the control system requirements for lifting entry will be suggested. Also,
5 the operational experience obtained during terminal guidance, navigation, and
6 landing, which should be applicable to lifting entry vehicles, will be
7 discussed.

8 RESULTS AND DISCUSSION

9 Entry Controls

10 Sixteen X-15 flights have been made, with two airplane configurations, during
11 which low dynamic pressures were experienced and entries were required for
12 recovery. The two configurations were (1) ventral fin on and (2) ventral fin
13 off. When the original ventral-fin-on configuration exhibited undesirable
14 augmentation-off control characteristics, the fin was removed. This resulted
15 in a somewhat lower directional stability but, more important, a configuration
16 controllable by the pilot throughout the flight envelope with the damping
17 augmentation inoperative.

18 The X-15 has reached altitudes up to 354,200 feet with apogee velocities
19 of about 4,500 fps. Entry angles of attack as high as 26° , recovery normal
20 accelerations to 5.5g, and dynamic pressures of 1,900 psf were obtained. One of
21 the two airplane configurations used was equipped with conventional aerodynamic
22 control systems with three-axis stability augmentation. The other configuration
23 had an adaptive rate command control system. Each airplane had reaction jets for
24 control at low dynamic pressure. In the adaptive control system, both the
25 reaction and aerodynamic controls are blended and are actuated through conventional
26 pilot controls. The X-15 reaction controls were designed to be used only when
27 the aerodynamic control surface effectiveness is not sufficient to maintain the
28 desired vehicle attitude. The basic system commands a roll acceleration of

1 5 deg/sec², and pitch and yaw accelerations of 2 deg/sec² for each of two
2 systems. The X-15 system is completely dualized to provide the requisite fail
3 safety for man-operated vehicles.

4 Reaction-control experience.- Flight experience at essentially zero dynamic
5 pressure during entry has been obtained with three reaction control systems:
6 a simple acceleration command control system, acceleration command with rate
7 damping, and a rate command system. For the piloted control system, of equal
8 importance are the effectiveness of the system configuration and the control
9 fuel used during the control task. Figure 3 presents the low-dynamic-pressure
10 portion of two X-15 entries from high altitudes with the pilot utilizing the
11 acceleration command reaction control system (fig. 3(a)) and the rate command
12 reaction control system (fig. 3(b)). Entry dynamic-pressure buildup to 600 psf
13 is shown. The control tasks were similar. The pilot was asked to hold the
14 heading angle to the desired value, the bank angle to zero, and the pitch angle
15 to zero until angle of attack equalled 20°, and then to hold angle of attack
16 constant.

17 The pilot's inputs for the manual acceleration command control system are
18 characterized by pulse-type operation, although the rocket thrust response is
19 proportional outside of the deadband. The pilots disliked the dead band in the
20 system because it made precise control difficult.

21 Although both control tasks were rated as satisfactory by the pilots, it is
22 apparent that the airplane motions in the low- and high-dynamic-pressure regions
23 for the rate command system are controlled much nearer to the desired values.
24 The pilot ratings, reaction control fuel used, and the dynamic pressure at which
25 the pilot last used the reaction controls for these entry control tasks were:

	<u>Acceleration command</u>	<u>Adaptive rate command</u>
Pilot rating	3	2
Fuel used	63 pounds	24 pounds
Dynamic pressure at last pulse	330 psf	180 psf

Significantly more fuel was used with the acceleration command control system for this entry; however, on the average, only small, insignificant differences in the amounts of reaction control fuel used with the various systems have been noted.

The reaction controls were used to much higher than expected dynamic pressures in these entries. Reaction controls have also been used effectively to damp airplane oscillations in other X-15 flights. It appears that the pilot was using the acceleration command controls to high dynamic pressure for this purpose (fig. 3(a)). From a piloting standpoint, in regions of low dynamic pressure the reaction damping augmentation was especially desirable. The X-15 acceleration command reaction control systems have been altered by adding rate damping.

In the adaptive control system, the reaction controls are automatically blended with the aerodynamic controls in a single control stick to provide attitude rate command and stabilization. The pilot does not directly fire the attitude rockets, since his control stick commands are rate commands. The blending is a function of the aerodynamic control effectiveness and occurs only when the aerodynamic controls do not provide the airplane response required by the augmentation system or by the pilot's commands.

Of interest to the reentry-vehicle designer will be the duty cycle to be expected of the reaction controls during entry. Entries have been made with both the manual acceleration command and the rate command reaction controls. The flight environment to which these controls were used is shown in figure 4.

1 The effectiveness of the X-15 reaction controls is about equal to the aero-
2 dynamic control effectiveness at a dynamic pressure between 50 psf and 100 psf.
3 At lower dynamic pressure, the reaction controls are expected to be used. In
4 a transition region, between a dynamic pressure of 50 psf and 150 psf, either
5 reaction or aerodynamic controls could be used effectively, whereas at dynamic
6 pressures greater than 150 psf, only aerodynamic controls are expected to be
7 used. However, the X-15 entry experience shows that the pilots consistently
8 elect to use reaction controls well beyond the equal effectiveness crossover
9 line. Reaction controls have been used at dynamic pressures as high as 400 psf
10 at altitudes slightly above 100,000 feet. This has resulted in a fuel usage
11 significantly in excess of that expected from an estimate of the duty-cycle
12 fuel requirement based on the equal effectiveness crossover.

13 Although the fuel required by the rate command system has not been
14 significantly different from that used with the direct manual reaction
15 controls, the average fuel used by either of the systems has been about
16 170 percent of the estimate based on the equal control effectiveness crossover.

17 What, then, are the features in a reaction control system that are desired
18 by the pilot for control during entry? Reaction augmentation is a requirement
19 for precise control of attitude in a low-dynamic-pressure environment. Dead-
20 band, a requirement for fueled reaction controls, is disliked by the pilots
21 since it precludes precise control. The X-15 pilots have endorsed the blending
22 of the aerodynamic and reaction controls activated by the same controller.

23 As a matter of interest, recent studies have shown favorable tradeoffs,
24 for using reaction controls as stabilizing devices, rather than aerodynamic
25 controls, to relatively high dynamic pressure; however, it appears that the
26 X-15 pilots are already using these controls to high dynamic pressures.

27 Aerodynamic controls.- Airplane designers have long sought a control
28 system that would provide acceptable control characteristics over the flight

1 envelope of the vehicle being designed. Of course, the design task becomes
2 more and more difficult for the entry-vehicle designer because of the increased
3 vehicle performance. Even the definition of an acceptable system is not
4 always clear. Yet, based on present experience and predicted future
5 requirements, attempts are being made to design acceptable control systems
6 for the future vehicles.

7 Description of the system: The MH-96 adaptive control system, the most
8 advanced flight control system ever flown, is now being flight tested in the
9 X-15 airplane. Some features of the system are:

10 Self-adaptive gain changing

11 Rate command

12 Automatic trim

13 Acceleration limiting

14 Hold modes

15 Automatic blending of aerodynamic
16 and reaction controls

17 Control-stick steering

18 Reliability and fail safety

19 These features will each be discussed briefly, as will the flight tests of
20 the system, in an attempt to indicate what aerodynamic controls will be required
21 for entry vehicles. The adaptive system design goals of independence from
22 configuration characteristics and gain scheduling for a particular flight
23 environment should be appropriate for all future vehicles. The design
24 concept of the adaptive control system is shown in figure 5. Control commands
25 are introduced to the hydraulic actuators through conventional mechanical
26 inputs and simultaneous electrical inputs to the model. The system operates
27 on the principle of using sufficient lead in series with a high forward loop
28 gain so that the response of the aircraft will be approximately the response

1 of the model. This will occur if the system response is 3 to 5 times faster
2 than the airplane response.

3 The self-adaptive gain-changing feature of the MH-96 adaptive control
4 system maintains the high gains necessary to insure model following and,
5 during operation in reduced-dynamic-pressure regions, activates the reaction
6 controls. By design, the system has dual channels in each axis so that if one
7 channel fails the gain changer compensates to the limit of its gain range,
8 thus providing nondegraded performance for some single failures. This feature
9 is very desirable for the X-15 because of the rapid changes in the operational
10 environment of the airplane.

11 The rate command feature of the adaptive system retracts a number of
12 conventional flying qualities, particularly in the pitch axis since aircraft
13 normally have an affinity for a fixed angle of attack. Rate command trim
14 is also used and is an obvious companion to rate command control.

15 Because the X-15 augmentation servo has limited control authority, auto-
16 matic trim is used to provide full surface authority for the adaptive system
17 by energizing the trim actuator so that the servo is permitted to operate
18 about its center position for all flight conditions. However, the automatic
19 trim would not be required if a full-authority servo were used in the system.

20 Normal-acceleration limiting is a design feature of the X-15 control
21 system that has not been required consistently during entry. The rate of
22 acceleration increase causes the pilot to react in anticipation of excessive g,
23 thus preempting the actual limiting action of the system.

24 Outer-loop pitch angle, angle of attack, bank angle, and heading hold
25 modes are a part of the X-15 control system. These modes have been used on
26 many of the extreme flights to enable the pilot to obtain more precise
27 flight data. The angle-of-attack hold mode with normal-acceleration limiting
28 insures safe recovery from the most severe X-15 entries.

1 The control-stick-steering mode of the adaptive system was designed to
2 allow the pilot to alter the hold attitude during hold-mode operation. This
3 mode, however, has not been used as intended, since the pilot can overpower any
4 of the automatic modes in the system. As a result, control-stick steering is
5 probably the least appreciated of the adaptive-system modes.

6 The automatic blending of reaction and aerodynamic controls discussed
7 previously is accomplished by activating the reaction controls when all
8 three axis gains reach 80 percent of maximum. Reaction controls, however,
9 are not used until commanded or required. The controls are deactivated when
10 all the gains decrease to 60 percent as the airplane enters aerodynamic flight.

11 For the X-15 application, extremely high reliability is a requirement
12 because of the low probability of a successful entry from high altitude without
13 augmentation. Fail safety is equally important since a large transient in a
14 high-dynamic-pressure region would result in the destruction of the airplane.
15 The redundancy configuration selected provides the generally incompatible
16 objectives of reliability and fail safety. Complete dual damper channels are
17 provided. The adaptive feature permits one channel to be lost with little
18 or no loss in system performance. The gain computers are interlocked, when
19 operative, to prevent overcritical gain following a limit-cycle circuit
20 failure and to provide the desired limiting effect for hard-over failures.
21 For model or other failures, conventional monitor circuits disengage both
22 channels when required. This problem, combined with the desire by NASA for
23 increased flexibility, led to the incorporation of a fixed-gain damper system
24 as a final backup system.

25 System flight experience: Except for specific flight tests to investigate
26 the operation of the adaptive control system and the controllability of the X-15
27 airplane, all flights have been conducted using the fully adaptive control
28 system, which includes the automatic gain changer. The channel gains have been

1 set as high as possible to avoid objectionable limit-cycle amplitudes. The
2 limit cycle results from the nonlinearities of the X-15 control-system
3 hardware and must be designed around. The pilots have rated the adaptive mode
4 of control as excellent. The system provides positive control and good
5 airplane damping throughout the aerodynamic flight envelope of the X-15
6 airplane, including entry flight. Controls blending has been endorsed by all
7 the pilots.

8 Although there was some speculation among pilots and designers on the
9 acceptability of the pitch-rate command control system, pilots have had no
10 problem adapting to this type of system for any phase of the altitude flight
11 from zero dynamic pressure to landing. Pitch-rate trim has not been so
12 readily accepted, however. It is a by-product of the system mechanization
13 and has been accepted as such, but it has necessitated the inclusion of an
14 extra display quantity--the longitudinal control surface position. With the
15 rate trim, the surface position is not related to the cockpit trim control
16 position.

17 Through the hold modes available to the X-15 pilot, an entire altitude
18 flight, except for landing but including entry, can be flown automatically.
19 With the rapid changes that occur during the X-15 flights, little time is
20 available to set the hold modes accurately. When there was insufficient time
21 to correctly trim to the desired hold attitude, the pilots have overpowered the
22 system. Some pilots have preferred to fly the prime control quantity, pitch
23 attitude, for example, and allow the system to hold bank angle and heading.
24 By design, the bank angle is held to zero if the hold mode is engaged when the
25 bank angle is less than 7° . Thus, this mode does not require a precise set-in
26 of the desired quantity.

27 The automatic trim provides full surface authority for the adaptive system
28 in regions of low dynamic pressure. For the short entry times of the X-15

1 airplane, it has not been possible to assess the effectiveness of this feature
2 of the system; however, for longer-time entries, a feature of this type should
3 be much more important for the conservation of reaction-control fuel.

4 The pilots consider the acceleration limiter to be a highly desirable
5 safety feature because the normal entry acceleration and the airplane structural
6 acceleration limit are close. For more extreme entries than have been flown in
7 the program thus far, the acceleration limiting feature would be necessary
8 since higher accelerations would be required for recovery.

9 The X-15 adaptive system has been very reliable. There has been only
10 one component failure in flight over a 2-year period of operation, which
11 includes 21 flights completely covering the flight envelope. This one
12 failure did not degrade the performance of the system, but caused only a small
13 bias in yaw detectable by the pilot as only a slight directional mistrim.
14 In 850 hours of total operating time on the flight system only seven component
15 failures have occurred, and five were the result of human error. This enviable
16 reliability record can be attributed to good design and solid-state electronics.
17 The system was designed and built around 1958-59 state-of-the-art components,
18 thus, subsequent improvements should make future systems more reliable.
19 Failures resulting from human error, however, will still present problems.

20 Control requirements study: A careful examination of the flight records
21 with the adaptive control indicates that the fully adaptive gain-changer
22 feature of the X-15 system may not be required for many flight regimes.
23 Recognizing that the simplest system may be the best, study was conducted
24 utilizing the complete six-degree-of-freedom X-15 simulator and breadboard
25 adaptive control system which could be altered as desired. Only the rate
26 command system at various forward loop gains with model following and reaction-
27 controls blending was used during a brief investigation of the controllability
28 of the X-15 during entries from 360,000 feet. The pilot's task was primarily a

1 pitch-axis task in which he was to hold an angle of attack of 25° until the
2 normal acceleration reached about 5g, and then hold 5g until level flight
3 was attained. Sideslip and roll attitude were to be held as close to zero as
4 possible. These entries (fig. 6) show very little difference in the pilot's
5 ability to perform the maneuver except for the entry at the lowest gain
6 setting in which larger deviations occurred in all three controlled parameters.
7 The pilot felt that excessive and continuous attention was required at the
8 lower gain, while the moderate-gain and adaptive-gain entries were acceptable.
9 These simulated entries compare well with an actual flight entry from
10 354,200 feet.

11 The results of this study are summarized in figure 7 in terms of pilot
12 opinion of the entry control task for each of the control systems investigated.
13 From these data it is apparent that successful entries can be accomplished
14 with either of the systems and that acceptable piloting performance and
15 ratings are obtained with the moderate fixed-gain rate command system. It is
16 interesting to note that the pilot ratings for actual flight are somewhat
17 better than those for the simulator. Also, the pilot stated that controlling
18 the airplane was somewhat easier in flight than on the simulator.

19 It should be remembered that the X-15 entry is severe from the standpoint
20 of rate of change of parameter and that it is conceivable that still lower
21 gain systems may be acceptable for higher-performance vehicles with longer-
22 time entries. Certainly, the fixed-gain concept should be considered for manual
23 control.

24 Design considerations: For the orbital lifting entry vehicle, the modes
25 of control required may be quite different from those of the X-15, inasmuch as
26 entry times are long and the entry angle is small. Some of the controls which
27 contributed to the success of the X-15 program may not be required. For example,
28 one feature, the adaptive gain changer, which initially prompted the adaptive

1 design concept may not be required for the lifting-entry vehicle. Perhaps
2 the most important reason for its inclusion would be for fail safety. Certain
3 system failures may occur with this system without degrading system performance.
4 For lifting entry vehicles, however, the pilot may have time to recognize
5 such system malfunctions and switch to backup modes, by virtue of the longer
6 entry time available.

7 The rate command control can provide satisfactory control and damping over
8 the wide range of aerodynamic characteristics from orbital speed to landing
9 and, so, appears to be the logical choice for the primary control system of
10 a lifting entry vehicle. The companion rate trim has not been so widely
11 accepted but, if properly mechanized, will provide acceptable trim. Full
12 utilization of the capabilities of the pilot or pilots would probably remove
13 the requirement for automatic trim, since some member of the crew could monitor
14 this quantity during the long entry times. Similarly, the acceleration-
15 limiting feature may not be required; the onset of acceleration for these
16 entries will be much slower than in the X-15 entry. During certain abort
17 situations, acceleration limiting may be desirable. However, detailed studies
18 of the mission and abort situation will be required to define the desired g
19 limiting.

20 Hold modes will certainly be desirable to reduce crew workload during the
21 entry and perhaps provide more precise control of flight path for energy manage-
22 ment and aerodynamic-heating considerations. Automatic blending of aerodynamic
23 and reaction control may not be required, inasmuch as time will be available
24 for crew switching. By monitoring such factors as control effectiveness and
25 fuel consumption, it should be obvious when switching is required.

26 Reliability and fail safety will be as vital in the design of this system
27 as in the X-15 adaptive system, however, in a somewhat different manner. Design
28 reliability must be based on much longer operating time for a mission, but

perhaps for fewer missions. Fail safety may not be so critical with relatively slow changes in controlled parameters; however, the design fail-safety philosophy applied in past manned-system design should be adhered to.

Navigation and Recovery

Ranging and navigation.-- As important for safe recovery as the control of the attitude of the vehicle for stabilization during entry is the control of the rate of dissipation of energy, or control of the range of the vehicle. Although ranging does not present the problem for the X-15 that will be presented by the orbital entry vehicle, similar controls must be exercised by the X-15 pilot for successful recovery of the vehicle after atmospheric entry.

The range of the most extreme X-15 entry made to date from launch to landing has been about 280 miles. During steep, short-time duration entries, the modulation of lift-drag ratio has very little effect on range (fig. 8) until recovery to level aerodynamic flight is achieved. During pullout, lift-drag ratio is sacrificed to maximum lift for recovery. Following pullout to level flight, the pilot controls range by modulating the vehicle lift-drag ratio or by turning flight. About 50 percent of the X-15 entry range capability is flown in aerodynamic flight and may be controlled by the pilot, whereas with the orbital vehicle about 1 percent of the total entry range is accomplished within the atmosphere. Certainly, cockpit display of the range capability of the vehicle during entry will be required for the orbital lifting entry vehicle. Such a display has not been required in the X-15; however, a mechanization is planned for use by the X-15 pilots in future flights.

The X-15 flights have been planned conservatively. A ground controller monitors the flights and, with precomputed range tracks and flight radar range data, suggests flight-path control changes to assure safe ranging of the airplane following an entry. By plan, all flights have been VFR. Although

1 much of the research information requested must be obtained by flying a precise
2 instrument flight plan, terminal ranging has been by visual piloting. Of
3 course, it is the pilot who must judge finally on the attitudes and configurations
4 flown. Missions are planned and practiced to acquaint the pilot with all
5 flight-plan variations likely to be encountered in flight. The pilots have
6 indicated that they can see the landing site from the maximum altitude attained,
7 350,000 feet, and from a range of 160 miles.

8 The X-15 entries have been planned with some 80 to 100 miles
9 excess range during the nonaerodynamic phase of flight and some 40 to
10 60 miles excess range in the aerodynamic phase (fig. 9). By modulating flight
11 path and lift-drag ratio, the pilots have had no difficulty arriving over the
12 landing site at a nominal high key of 20,000 feet and a Mach number of 0.8.
13 On only one occasion has the recovery been marginal (dashed line, fig. 9).
14 In this situation, the pilot, engrossed in checking onboard systems, ballooned
15 slightly during pullout and nearly overflowed the landing site. But, with a
16 call from the ground controller, he performed a steep turn and was able to
17 land on the south end of the lake rather than on the north lakebed as planned.

18 Key controls for the control of range have been angle of attack and speed
19 brakes. By flying the angle of attack for maximum lift-drag ratio, the pilot can
20 achieve maximum range, and by modulating speed brakes and through turning
21 flight minimum range is obtained. Although the effectiveness of the speed
22 brakes (approximately equal to the $\alpha = 0$ drag of the vehicle) in reducing
23 range is considered to be satisfactory by the pilots, they have expressed a
24 desire for more flexibility in operating the brakes. The present brake system
25 is relatively slow acting, about 5° of brake deflection per second. A faster-
26 acting speed brake would allow more precise control of range in the approach to
27 landing. In addition to being used as a range-control device, the speed brakes
28 have been used to increase the directional stability of the airplane in flight

1 attitudes where the level of stability was critical. Also, they have been
2 used to modulate overall performance to enable the pilots to obtain more
3 precise flight research data.

4 With the X-15 there have been no ranging and recovery problems in
5 operating by visual flight rules (VFR). Terminal navigation has been by
6 contact flight with ground monitoring. The requirement for contact flight for
7 orbital entry would be completely impractical using procedures proven during
8 the X-15 program. Certainly, entry and recovery by instrument flight rules (IFR)
9 is not out of the question, although it will require operation methods and
10 piloting displays or automatic systems not yet operational. However, IFR entry
11 with VFR recovery is practical now and would require a clear weather recovery
12 area of about 200 miles around the intended landing site.

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1 Recovery.- Successful recovery of an entry vehicle requires a safe landing
2 at the desired landing site. In 1958, a program was initiated specifically to
3 determine a satisfactory technique for accurately and repeatedly landing low-
4 lift-drag-ratio airplanes, in particular, the X-15. The low lift-drag ratio and
5 high wing loading of these airplanes combine to produce, in the landing approach,
6 one of the most challenging aircraft to land.

7 Since the steep approach of entry vehicles has defied successful simulation,
8 a flight program was initiated with airplanes having similar characteristics.
9 This program proved to be of great value to the pilots. It acquainted them with
10 the approach and landing expected of this class of vehicles. Now, after about
11 100 landings with the X-15, the landing has become routine and actual spot
12 landings are requested of the pilots. These requests serve two purposes: they
13 help prepare the pilots for emergency landings and they provide data on the
14 landing requirements for future vehicles. Actual landing dispersion with the
15 X-15 (fig. 10) has been only slightly greater than with other high-performance
16 airplanes. Considering the zero point as the desired touchdown point, actual
17 touchdown has occurred within $\pm 2,500$ feet of this point and 70 percent of the
18 landings have occurred within $\pm 1,000$ feet of the zero point. Actual slideout has
19 ranged from about 4,000 feet to 8,700 feet. Although the pilot has little control
20 over the directional divergence of the X-15 below 100 knots, lateral slideout
21 has nominally been about 200 feet, but values as high as 2,000 feet have been
22 recorded for crosswind landing on a damp lakebed. However, with effective
23 nosewheel steering, it appears that low-lift-drag-ratio gliders with speed brakes
24 for drag modulation could be landed successfully on 2 to 3 mile runways. Touch-
25 down vertical velocity has averaged 3.4 feet per second with a range of 0.5 to
26 9.5 feet per second.

27 Most of these approaches have been from a high-key position of 20,000 feet
28 and a Mach number of 0.8 with a circular overhead approach pattern. This type

1 of approach has been preferred for visual landing approaches, such as all of the
2 X-15 approaches have been. The straight-in approach has the advantage of
3 reducing pilot judgement requirements, necessitating only drag modulation to
4 insure the proper airspeed. Instrument approaches with these vehicles may
5 require straight-in approaches or perhaps some technique not yet developed.
6 Certainly, new displays will be required for these steep approaches and high
7 landing speeds.

8 Of somewhat more importance for the lifting entry vehicle than for the X-15
9 airplane is the question of what external visibility is required to land low-
10 lift-drag-ratio, high-wing-loading vehicles, since the problems of heat pro-
11 tection will be much more complex than those of the X-15. The X-15 pilot has
12 180° of peripheral vision and about 17.5° of forward vision, including 10° up and
13 7.5° down. With this field of vision and with the assistance of an escort air-
14 plane, the X-15 landings have become routine. Actually, in the landing attitude
15 the pilot's downward vision is limited to about 0° by airplane attitude. Two
16 landings have been made with reduced vision on the right side when the cockpit
17 glass shattered as a result of aerodynamic heating. For one of these landings,
18 the entire side glass panel was completely obscured.

19 Entry Simulation

20 In preparation for the X-15 program, several simulation programs were
21 conducted to prepare the pilots for the extreme altitude and speed mission of
22 which the X-15 is capable. As the program has progressed, the fixed-base
23 simulator has been relied upon heavily for the many operational aspects of the
24 program. The simulator has been used by the pilots to practice each flight.
25 Therefore, as a by-product of the program, data have been obtained to help
26 define the simulator requirements for high-performance airplanes. A comparison
27 of the pilot's opinion of the control task in flight and on the fixed-base
28 simulator has been obtained for the entry control task following each flight.

1 Figure 11 compares the pilot rating of flight and simulator. As expected, the
2 flight control task was rated slightly higher than the same flight on the fixed-
3 base simulator, inasmuch as none of the kinesthetic cues of flight are duplicated
4 on the simulator. However, the mechanics of the entry control task on the simu-
5 lator was rated similar to the flight control task.

6 Although the initial X-15 pilots were exposed to the entry control task on
7 a moving-base simulator which duplicated the entry acceleration environment, the
8 pilots do not feel it necessary to prepare for the X-15 flights by being exposed
9 to the predicted accelerations. Exposure to the expected acceleration did give
0 them confidence that they could perform the control task under the acceleration
1 environment, but the performance of pilots without the centrifuge experience
2 has been acceptable, even on their first flights.

3 Aerodynamic Heating

4 Although aerodynamic heating has not been a problem on any of the X-15
5 entries with the design temperature of 1,200° F, predictions of the aerodynamic
6 heating on the airplane have been made for each of the altitude entry missions.
7 In fact, more severe heating has been encountered during heating research flights,
8 which allow greater flight time in the high heating regions of high speed at high
9 dynamic pressure. The temperature-prediction process developed for this program
0 involves three digital computer programs. First, the local flow is computed for
1 the conditions expected during the flight. The computed local flows are used
2 to calculate the aerodynamic heat transfer to the airplane surfaces. Then, the
3 differential equation describing the time-dependent heating of the thin-skinned
4 areas is integrated to give skin temperature as a function of time during the
5 flight. Finally, the aerodynamic-heating inputs are used to calculate the
6 transient heating of internal structural areas where heat transfer is by con-
7 duction and/or radiation.

8 Figure 12 compares the calculated and measured wing temperatures during an

1 X-15 altitude flight to 315,000 feet. The present calculated methods were
2 arrived at by using empirical coefficients developed to modify the basic theo-
3 retical calculations and improve the actual prediction process. Temperatures
4 several hundred degrees higher have been measured during heating research
5 flights. The X-15 entries made to date are not temperature-limited as orbital
6 entries would be expected to be; however, temperature-prediction methods for the
7 X-15 appear to be acceptable and should provide methods for predicting the aero-
8 dynamic heating of the orbital entry vehicle.

9 Additional Contributions of the X-15 Program

10 In addition to the operational contributions to the entry technology already
11 discussed, the X-15 program has made many other contributions, although perhaps
12 more subtle. For example, at least up to Mach numbers of 6, the measurement and
13 prediction methods used to determine the stability and control derivatives of
14 complicated configurations have been verified with actual flight-determined
15 derivatives. Both pilots and designers have gained increased confidence in the
16 methods of predicting handling qualities and the levels of stability required at
17 hypersonic speeds. All of the maneuvers required of entry vehicles have been
18 performed by the X-15 pilots using a side-located controller in an acceleration
19 environment as hostile as would be expected during orbital entry. Airplane
20 systems have been designed and made to function in all the environments that
21 will be operational for the lifting entry vehicle. Pilots have proved that the
22 human can control effectively in many flight regimes from 0 g to high g. For
23 the X-15 program, the pilot was integrated into the design far earlier and more
24 completely than with any previous design. The success of this program attests
25 to the wisdom of including the pilot in the program at its beginning. Although
26 the degree of aerodynamic heating at some locations on the airplane was predicted,
27 other locations sustained heat damage during routine flight. Locations such as
28 landing-gear doors require much better seals than originally believed. Also,

1 junctures where the boundary layer was tripped resulted in much higher heat loads,
2 sometimes buckling the thin skin. Skid-type landing gear proved satisfactory;
3 however, this type of gear, it appears, required a new design criteria because of
4 the radically different rebound reaction loads that are experienced with the gear
5 in this location. At high performance it was shown that assistance other than
6 VFR was required for safe recovery in some critical regions of range control.
7 Finally, the X-15 program has demonstrated that a buildup flight program in which
8 flight and system operational experience can be gained pays large dividends in
9 providing a more successful overall operation.

10 CONCLUDING REMARKS
11

12 Sixteen successful X-15 entries from high altitudes, the most extreme of
13 which was from 354,200 feet, have provided confidence that lifting entries can
14 be made with higher-performance entry vehicles.

15 Controls, displays, and operational methods have been developed that made
16 short-time, steep entries feasible--entries that are predicted to be more severe
17 from a controllability standpoint than entries with a lifting entry vehicle. The
18 contact flight ranging and recovery of the low-lift-drag-ratio, high-wing-
19 loading X-15 airplane have become routine.

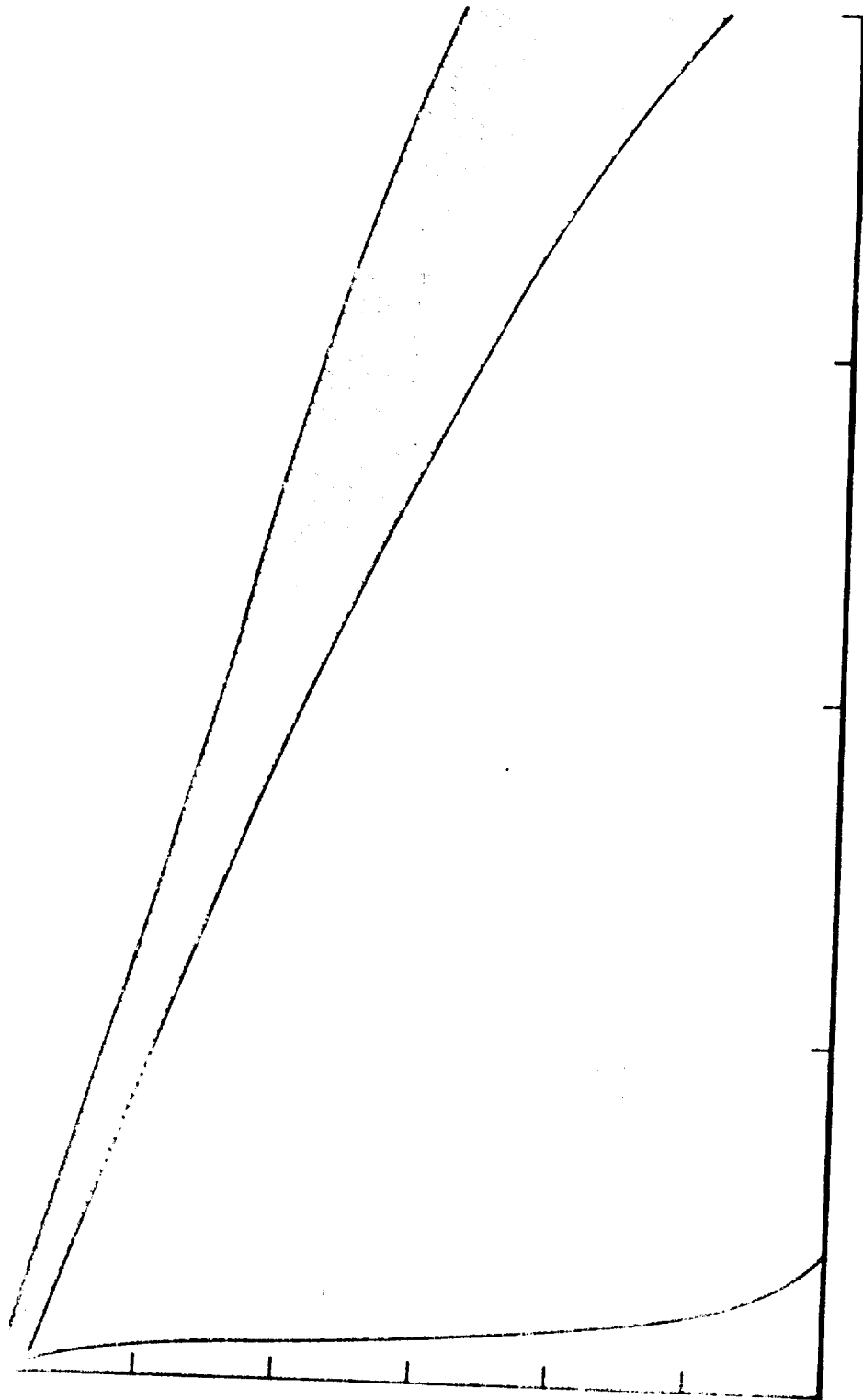
20 Although instrument flight recovery of lifting entry vehicles is feasible,
21 some research effort will be required to develop operational methods and required
22 displays.

SYMBOLS

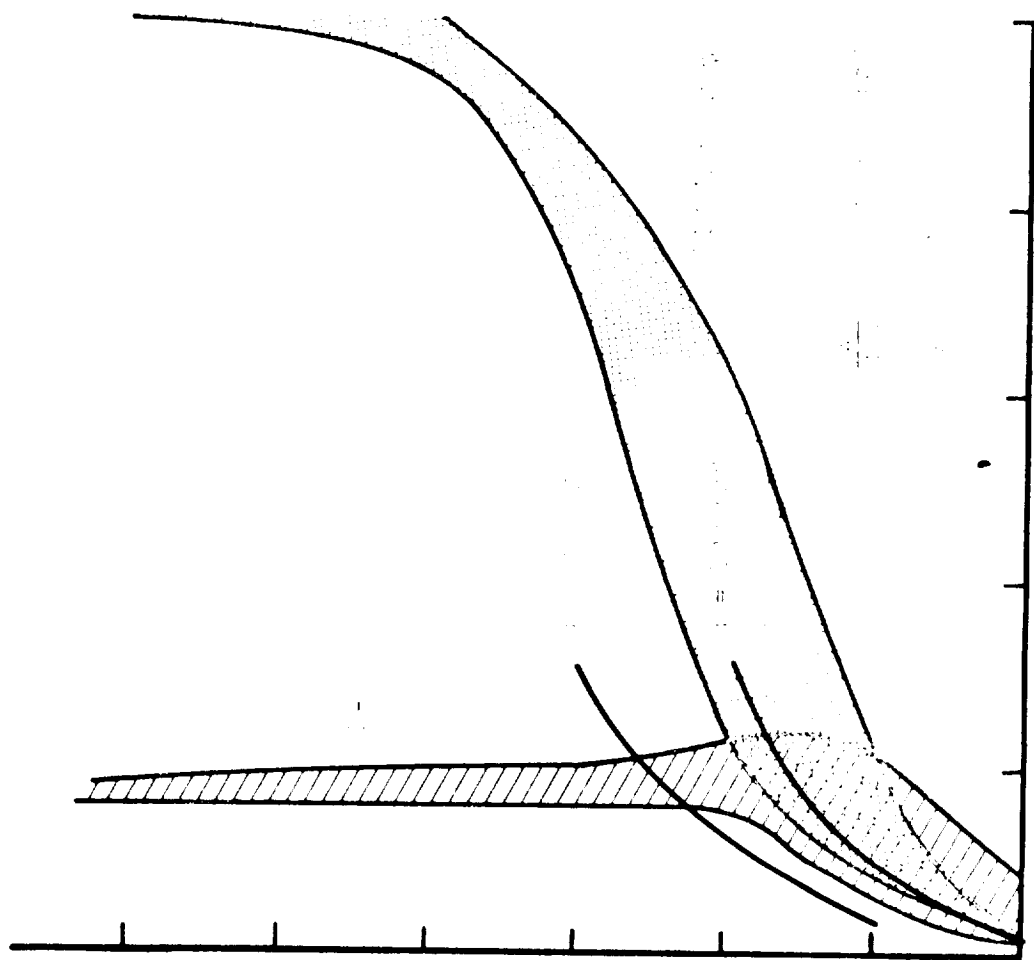
A	reference area, sq ft
C_L	L/qA
D	drag
g	acceleration due to gravity
h	altitude, ft
h_{max}	maximum altitude, ft
K_p	roll-channel gain, deg/deg/sec
K_q	pitch-channel gain, deg/deg/sec
K_r	yaw-channel gain, deg/deg/sec
L	lift
q	dynamic pressure, psf
t	time, sec
W	weight, lb
α	angle of attack, deg
θ	pitch angle, deg
ϕ	bank angle, deg
ψ	heading angle, deg

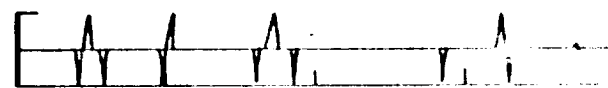
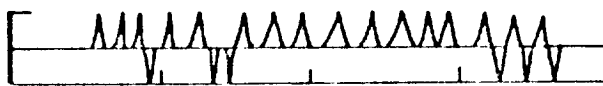
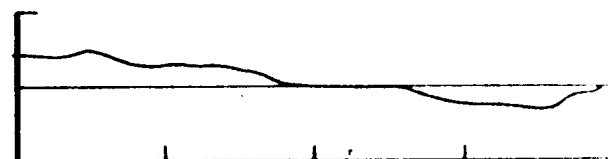
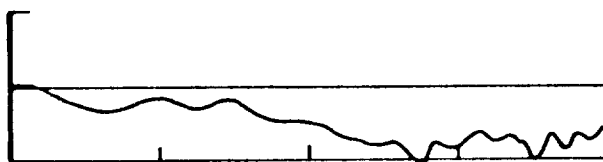
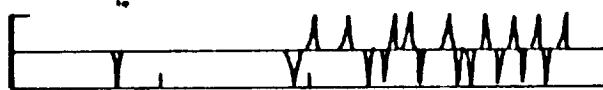
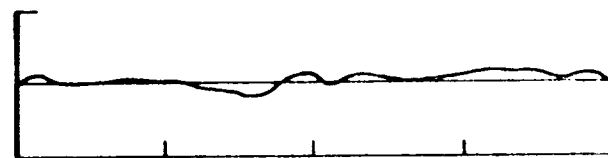
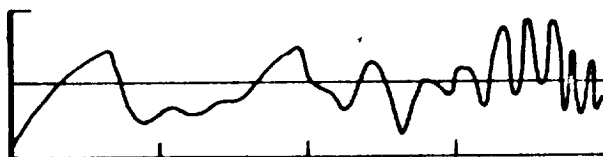
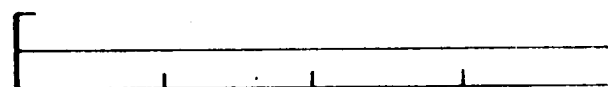
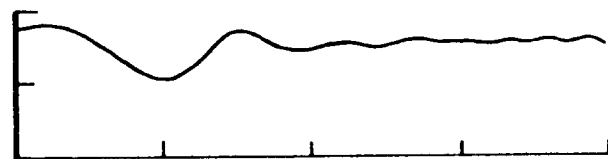
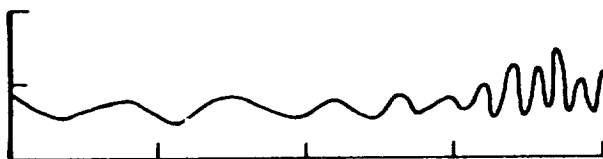
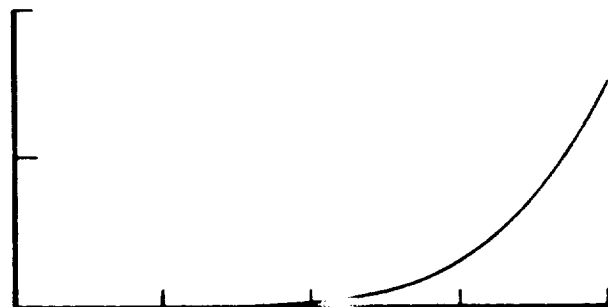
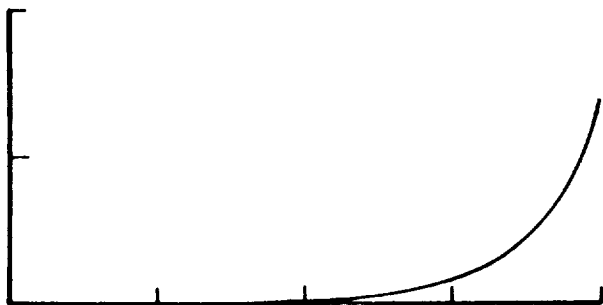
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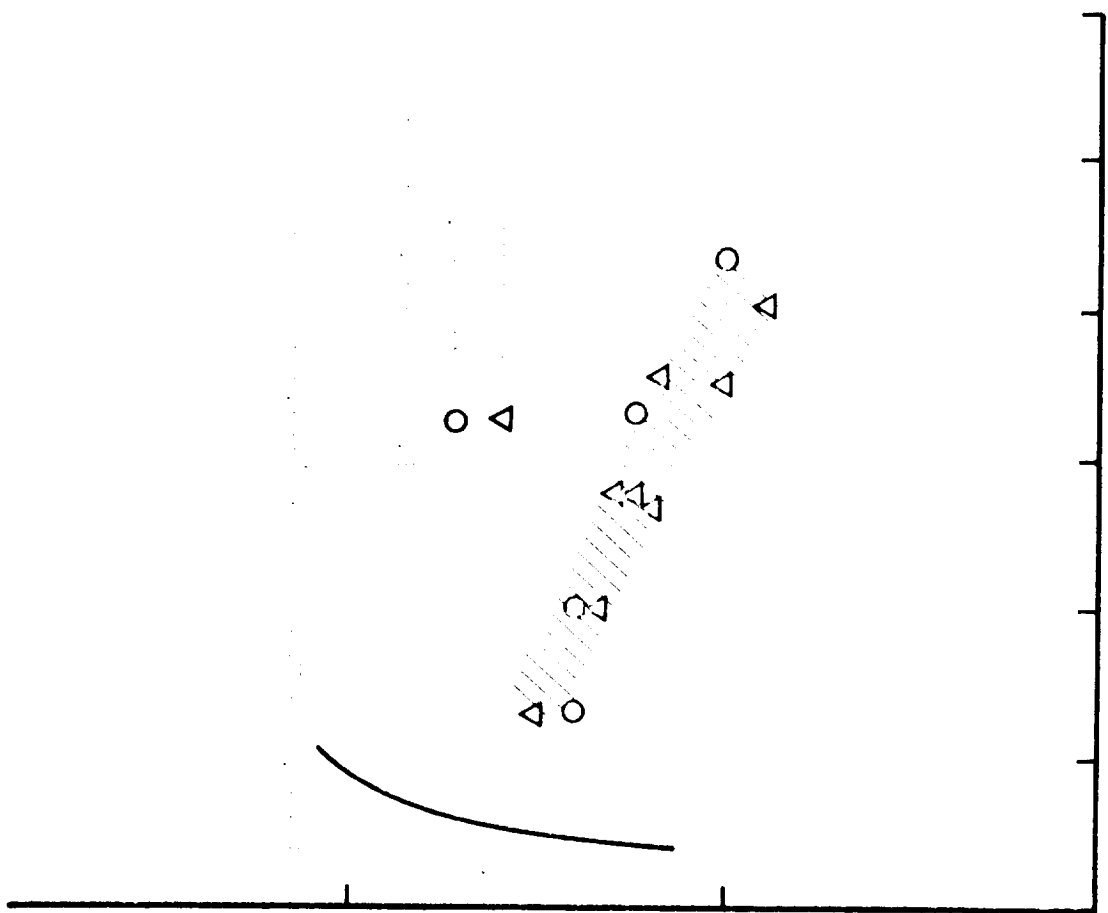
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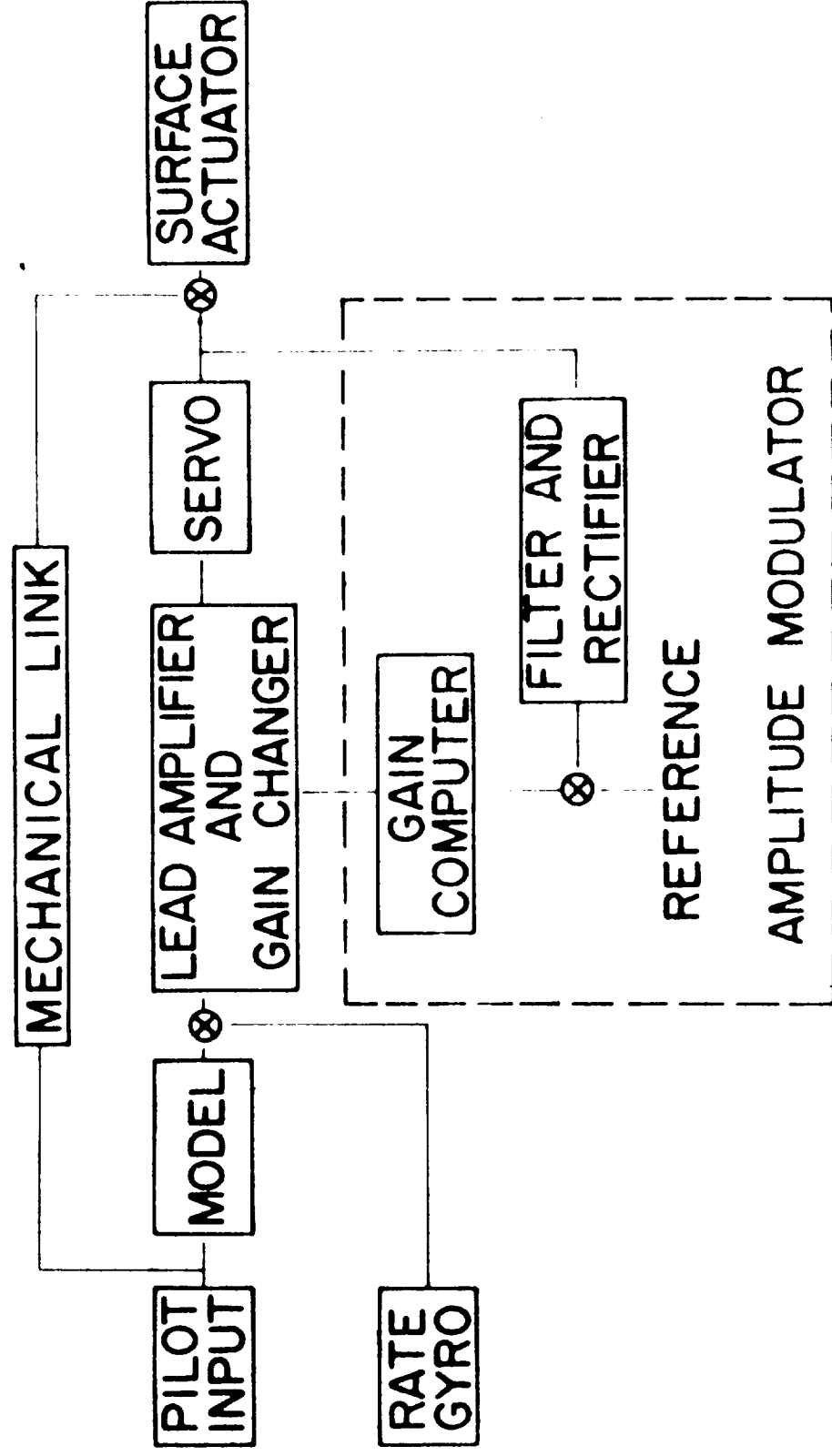
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MH-96 ADAPTIVE CONCEPT



CONTROLLABILITY DURING X-15 ENTRIES FOR VARIOUS DAMPER GAINS

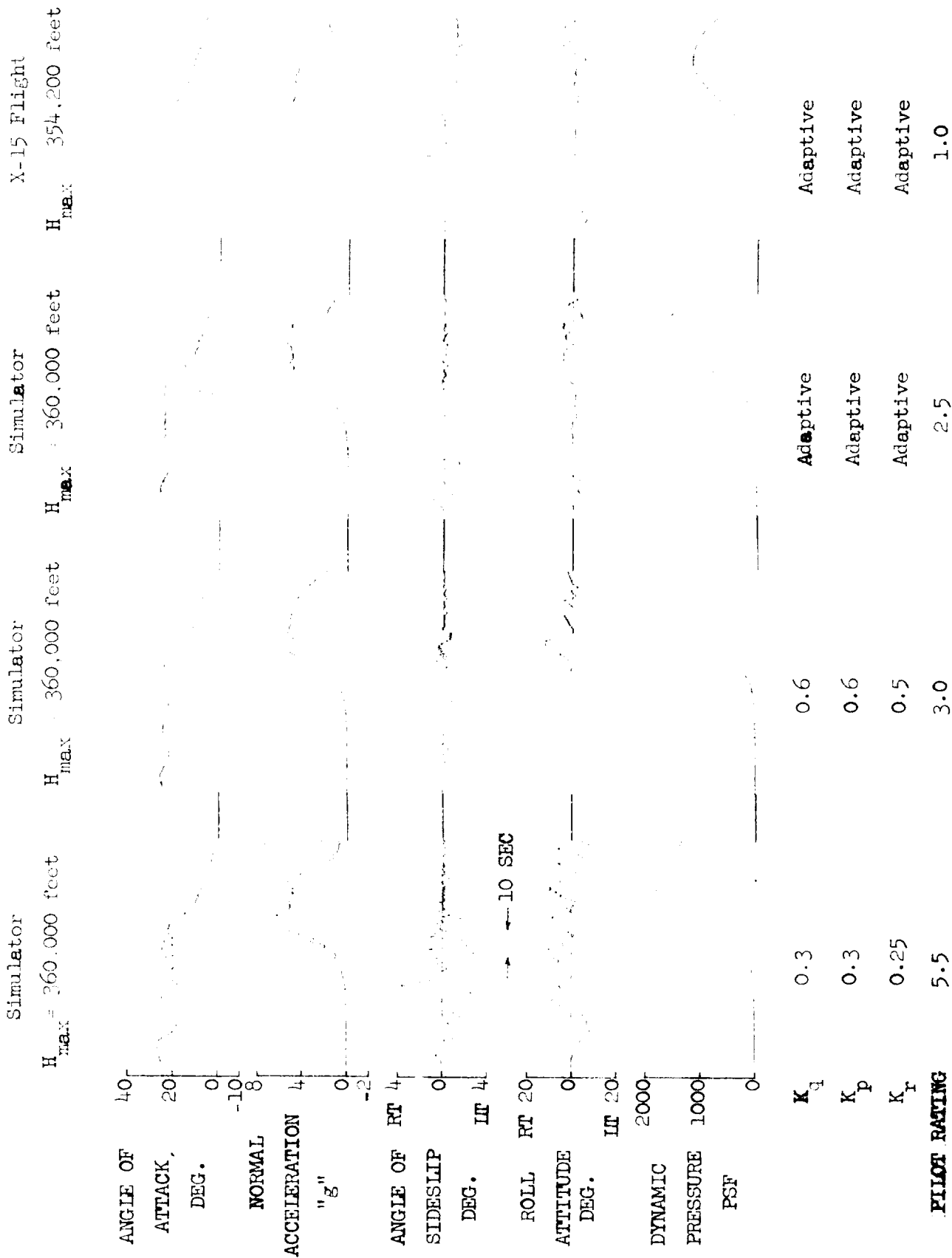


Figure 6

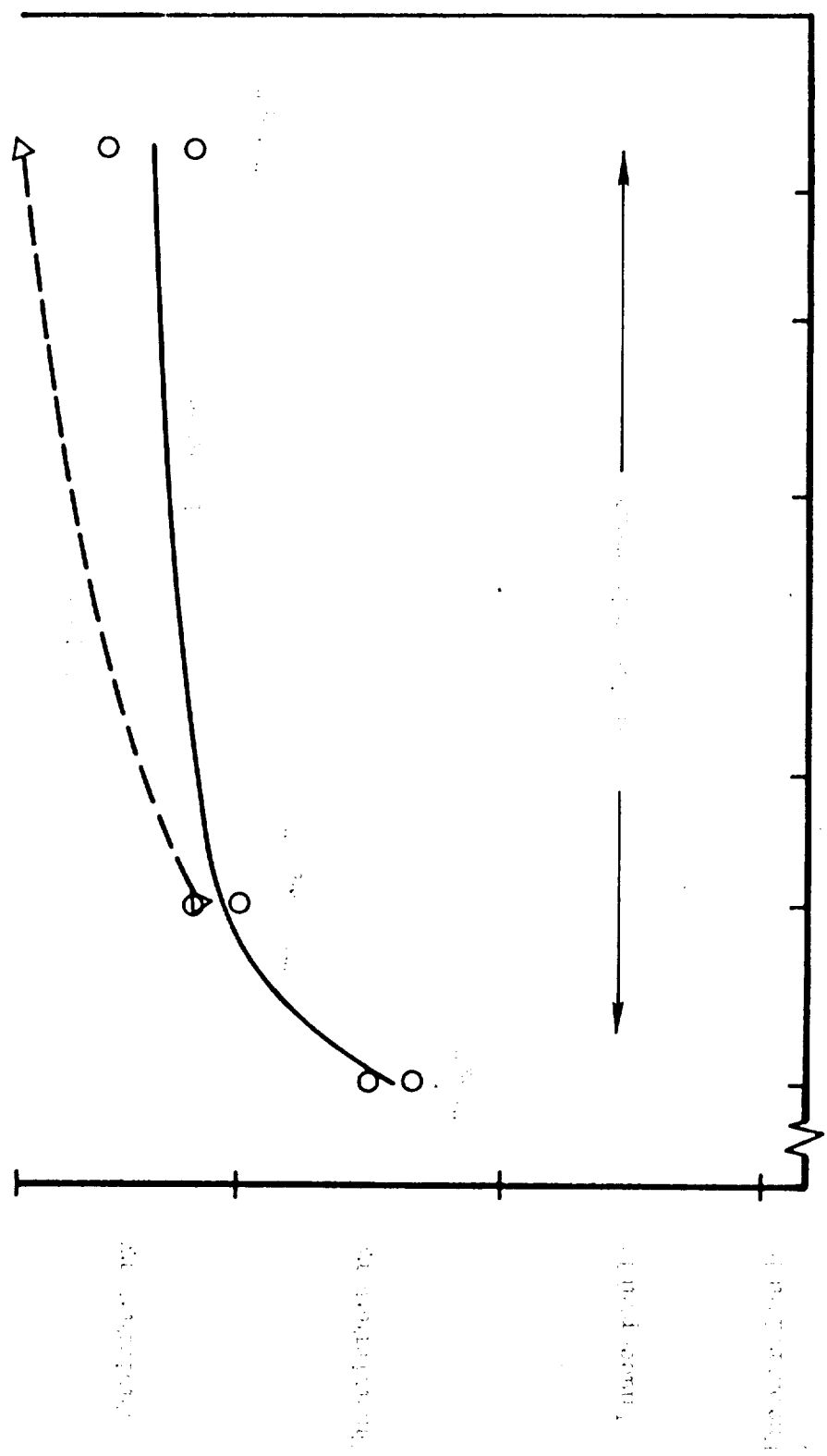
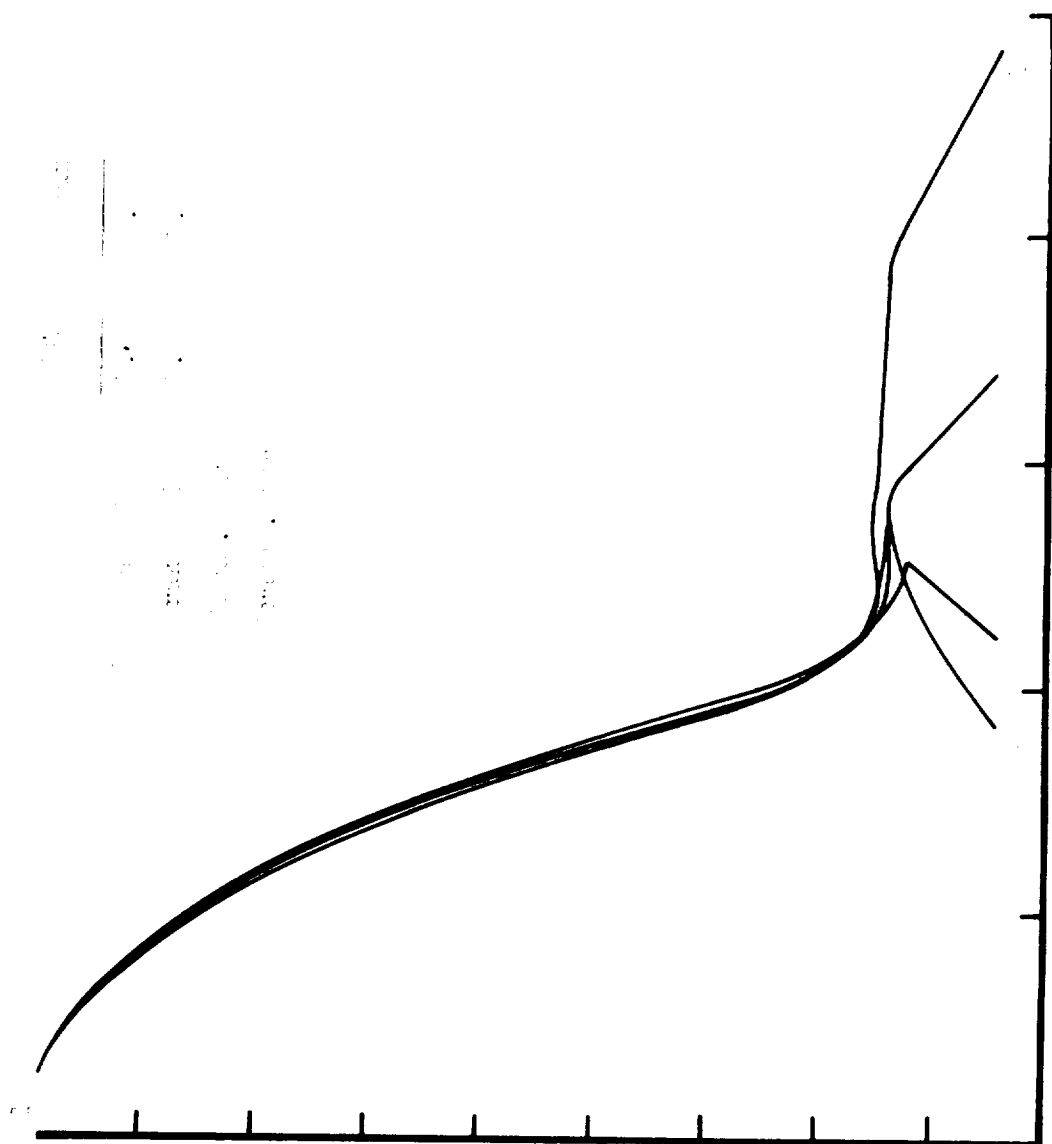
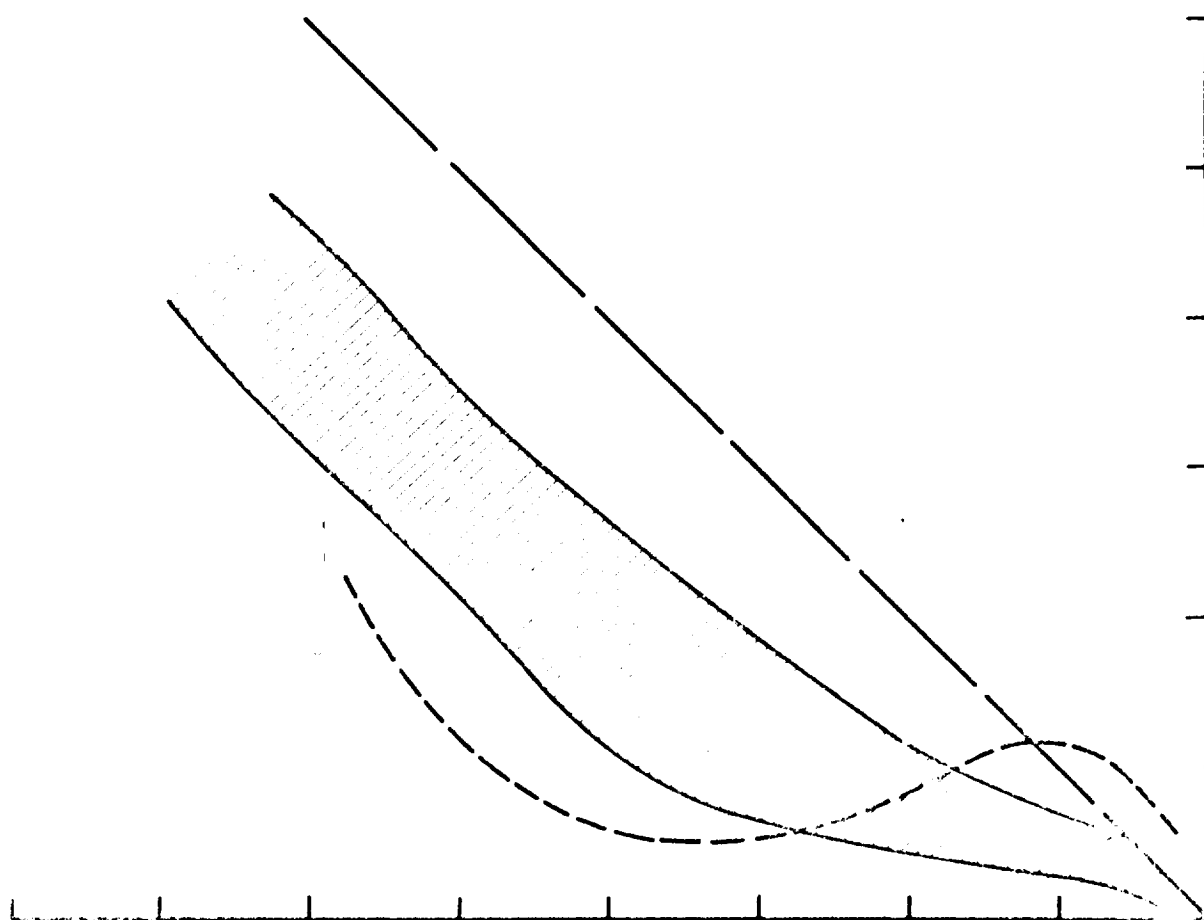
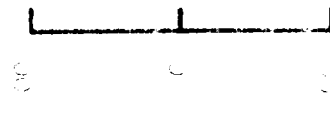


Figure 1







actual
frequency,
m

Empirical frequency



Theoretical frequency



Frequency

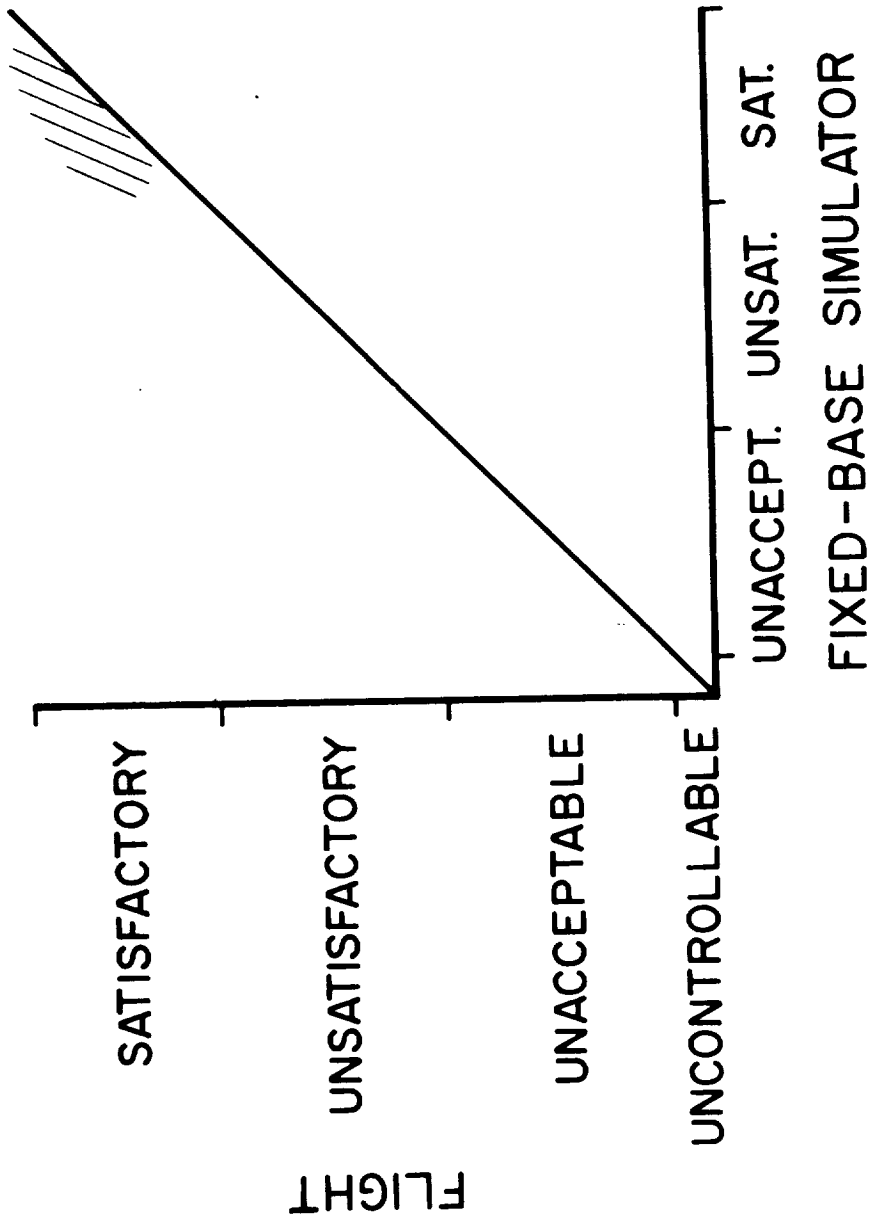
Empirical frequency

Theoretical frequency

Frequency

CORRELATION OF FLIGHT AND FIXED-BASE SIMULATOR

REENTRY



COMPARISON OF CALCULATED AND MEASURED TEMPERATURES

FLIGHT TO 315,000 FEET

